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Development of a New Instrument for Direct Skin Friction Measurements

Prepared for

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SUMMARY

A new instrument has been developed for direct measurement of wall shear stress generated by flows. This device is described in this report with typical measurement results. This instrument is simple and symmetric in design with optional small moving mass and no internal friction. Features employed in the design of this instrument eliminate most of the difficulties associated with the traditional floating element balances. This device is basically small and can be made in various sizes. Vibration problems associated with the floating element skin friction balances have been found to be minimized due to the design symmetry and optional damping provided. The unique design of this instrument eliminates or reduces the errors associated with conventional floating-element devices: such as errors due to gaps, pressure gradient, acceleration, heat transfer and temperature change. The instrument is equipped with various sensing systems and the output signal is a linear function of the wall shear stress. Dynamic measurements could be made in a limited range and measurements in liquids could be performed readily. Measurement made in three different tunnels show excellent agreement with data obtained by the floating element devices and other techniques.

I. INTRODUCTION

Throughout the years the importance of viscous effects in aerodynamics has motivated a great number of both theoretical and experimental investigations in the field of boundary layer flows. particular attention has been given to the frictional forces introduced by these effects on the surface of moving bodies. For the laminar boundary layer the theoretical evaluations of the frictional forces has reached a well advanced stage. But for turbulent boundary layer there is not a generally accepted theory to predict accurately the frictional forces. In particular the skin friction associated with the turbulent boundary layer presents an important problem today. Correct skin friction measurement not only can serve to offer vital information but also can be used to check the accuracy of theoretical modeling techniques.

Direct measurement of skin friction was originally an essential step in setting-up basic skin friction laws. Direct measurements of skin friction by Kempf (Ref. 1) in 1929 and others (Ref. 2, 3, 4, 5 & 6) later formed the basis for the generally accepted skin friction estimation for incompressible flow. However, because of our limited understanding of turbulent flows there has been the need to extend direct skin friction measurements to compressible flows. In many circumstances there exists no theory, even experimental measurements are not simple. For example, in flows with strong pressure gradients and unsteady flows, accurate skin friction measurements are difficult or impossible.

All aerodynamic experimentalists are well aware of difficulties associated with the direct measurement of skin friction. Most of the existing skin friction data have been obtained through indirect methods such as Preston tube, surface hot film, boundary layer velocity profile measurements, etc., instead of direct measurements. There are many difficulties and limitations associated with the application of these indirect techniques and moreover, these are approximate approaches.

The knowledge of skin friction distribution on models at high Reynolds numbers is extremely helpful for the accurate prediction of aerodynamic loading and performance, determination of transition point, region of flow separation and other flow characteristics. Because of the limitations associated with the prediction techniques, direct measurements of skin friction is the only accurate way to identify the shear stress loading at critical points

on realistic bodies.

In the last decade tremendous progress in the computational aerodynamics has been accomplished. Often the accuracy of numerical models are tested against experimental results especially in regions of strong gradients in the flow. Obviously reliable and accurate experimental data are investments of high gain. It is therefore necessary to improve the experimental level of the aerodynamic data in regions of insufficient or inaccurate data availability. The significance of a simple and functional instrument, for direct measurement of local shear stresses, is evident.

Most of the conventional direct skin friction force measuring devices are very similar in concept and fundamentals of operation.

There are some more elaborate designs in order to compensate for some of the commonly known difficulties. K. G. Winter (Ref. 7) described some of the problems associated with the direct skin friction measurement devices. The Naval Ordinance Laboratory (NOL) balance (Ref. 6) is one of the most accurate skin friction measuring devices. The NOL balance is based on the same principle of a one time commercially available Kistler's balance (Ref. 7). Our skin friction transducer was designed and manufactured as an alternative to eliminate the troubles we encountered with the NOL balance. It has proved to be a very capable instrument with great potentials as discussed later. Detailed description and advantages of the belt instrument is given in the next section, and in the paper by Vakili and Wu (Ref. 8). An important feature of this transducer is its ease of handling and simplicity of calibration and measurements.

It is obviously desirable to have a small skin friction transducer so that one or more of them can be embedded onto a model surface for direct local skin friction measurements. Similar to pressure, temperature, velocity data etc., skin friction data on a model has significant applications. So far the problem has been the lack of a reasonably small size transducer. We now believe that our device would eventually fulfill the requirements.

At the present our instrument is relatively small 1" wide, 1.48" long, 1.5" deep (2.54 cm x 3.76 cm x 3.81 cm) compared to other direct skin friction instruments. However, using optical techniques for the detection of the strain or deflection of the flexures would enable further reduction of

the total size. So far there has been no need for real miniaturization of our device. Miniaturization would result in a small area of the instrument to be used to measure the wall shear stresses. This in turn results in smaller forces, therefore, high precision sensing techniques (especially optical) are needed to measure small loads and maintain sufficient accuracy and need to be investigated further for applications in (the miniature size of) this transducer.

II. DESCRIPTION OF THE BELT SKIN FRICTION BALANCE

Principles of Operation

The Belt Skin Friction Balance (BSFB) consists of a flexible belt (tape) wrapped continuously and tightly over two cylinders separated by a small distance. The cylinders are mounted on frictionless flexures which are supported at the ends in a solid housing. A portion of the belt replaces the surface over which the fluid flows. The belt can be replaced with belts of different materials and surface finishes, for measurements of surface shear stress on the corresponding surface environment.

The shear stresses applied by the fluid to the belt causes the cylinders to rotate (the amplitude of rotation is designed to be less than three degrees). The incremental rotation of the web is directly related to the shear stress applied to the belt by the fluid. Strain gauges are installed on both sides of the flexure web to measure the amount of deflection. Each flexure, having no backlash and requiring no lubrication, is double end supported and made from a pair of stainless steel flat, cross-springs supporting rotating sleeves. Figure 1 shows a schematic diagram of the inner details of the BSFB instrument, this figure is also demonstrating the principle of operation of the BSFB. Figure 2 shows the details of a more compact version of the same instrument with dimensions of: 1" wide ,1.48" long and 1.5" high. Different size and range instruments are required for accurate measurement of the shear stress loads encountered in various flows to provide good sensitivity and resolution.

For each particular instrument the stiffness of the flexure webs are selected such that, the angular deflection for the expected maximum force exerted on the area of the belt exposed to the fluid is not more than three degrees. The commerically available flexures are manufactured to provide

frictionless pivots for limited angular travel which automatically prevents them from being damaged by overloading.

Because of the necessary movement of the belt, it is essential that there be a small gap (clearance) around the belt. This corresponds to the gaps around the floating element of the common balances. Since the belt moves on cylindrical (circular) path there is no change in the clearance dimensions created during measurements. There is no evidence that the presence of these gaps influence the accuracy of the transducer. There is also no particular requirements on the gap dimensions, except that the belt must move freely without contact with the top surface and sides to ensure frictionless operation. The presence of the gaps allow for pressure equilibrium on both sides of the belt's exposed surface. This is of particular importance for measurements in flows with transient behaviour or with pressure gradient. In this respect a finite gap is realistically desirable to allow instantaneous equilibrium.

The gaps created by the necessary clearance between each cylinder and the top surface also depend on the manufacturing and the assembling precision. These gaps have been kept to a minimum in the present instruments. It is interesting to note that for small deflections of the flexures no change in these gaps is made.

Strain Gage Sensing Technique

Electrical resistance strain gages are used frequently to measure strains on mechanical elements in form of electrical signal. This technique is well developed and quite accurate measurements are being made using wide varieties of strain gages. In the present transducer, foil type strain gages have been installed on the flexure webs in order to convert the wall shear stresses on the belt surface to electrical signal. There are two strain gage bridges installed one on each flexure, with the two bridges connected in parallel. This provides for reduced disturbance effects which may be resulted by rotation of the two flexures in opposite directions.

Even though strain gages are widely used, there are some limitations associated with their use. In general, environmental changes, such as the ambient temperature effects the resistance of strain gage which in turn produce erroneous strain gage output not necessarily related to the designed

conditions. To minimize this, normally strain gage bridges are temperature compensated for a reasonable range of temperature variations. However, it is also common practice to calibrate the temperature effect on the whole transducer, since full compensation for a very wide temperature range is frequently almost impossible.

Optical Sensing Technique

We have also developed an optical sensing technique to replace the strain gauges and to eliminate some of the associated problems (like temperature effect). Using fiber optics it is possible to directly detect the translation of the belt due to the (shear stress) forces applied to the measuring surface. The optical arrangement is shown in Figure 3 a,b. The amount of light backscattered from a special geometry reflective surface is related to the relative position of that surface. In a bench experiment, infrared light was directed on to the reflective surface and the back-scattered light was sensed by a light sensitive transistor. The voltage output was proportional to the reflected light which is in turn proportional to the displacement of the surface reflecting the light (Ref. 8).

The local optical technique is incorporated into the instrument from the opposite side of the measuring surface, therefore no form of interferences is expected in the flow. There also exists the possibility of displacement detection remotely, through interferometric techniques, which is yet to be investigated. Using these optical techniques shall make a significant reduction of the instrument size readily possible.

Vibration Effects

The effect of vibration on the instrument is minute, however, because of the amplification of the signal the vibration effect is also amplified parallel to the force signal. But, since the vibration effect is symmetrical it can be separated from the (force) signal by averaging or filtering the output (Ref. 9). There was no need for damping for all of the measurements reported here. In this respect it is not necessary to provide damping except in very harsh environments.

To reduce the vibration sensitivity, damping can be provided by viscous oil in the damping gap provided for this purpose (Figure 1). The result of

damping provided in this manner is extremely satisfactory. The viscosity of damping oil may change due to temperature changes. Therefore, it is recommended to use an oil to provide a proper viscosity for the conditions of measurements. The oil damping technique may be replaced by magnetic or other means. This is essential, since at certain measurement conditions (i.e., for low temperatures) oil cannot be used as a viscous fluid.

Calibration Procedure

Because of the symmetrical design of the instrument, it could be used at any orientation. To calibrate the instrument it is held such that the sensing surface is vertical, and dead weights are hung at one end of a very thin nylon thread that is attached to the sensing surface. The output of the transducer is recorded for different dead weights in order of increasing and decreasing weights to make sure of the perfect linearity of the instrument. A sample calibration curve for this transducer is shown in Figure 4. The slope of the calibration line depends on the flexure stiffness and the sensitivity of the strain gages, which are design parameters and are built into the instrument.

III. MEASUREMENT FACILITIES

1. Unitary Plan Wind Tunnel

The Langley Unitary Plan Wind Tunnel is a closed-circuit, variable-pressure Facility with two variable Mach number test sections which are approximately 1.22m in height and width and 2.13m in length. The Mach number ranges of the two sections are 1.46 to 2.80 and 2.30 to 4.63. Detail description of this tunnel is given in Reference 10. The nominal test section unit Reynolds number is 6.5×10^6 per meter. The test section stagnation pressure and temperature are controlled to vary the Reynolds number. Present measurements were performed in the first test section, with the lower Mach number range, at a nominal Mach number of 2.16 for various Reynolds numbers.

2. 0.3m Transonic Cryogenic Tunnel

This tunnel has a two dimensional test section $20 \times 60 cm$ with the operational parameters as listed in table below (the data on this chart is taken from Reference 11. The 20 cm side wall is slotted and the 60 cm

wall is solid. The solid wall was used as a flat plate on which the various transducers were measured. More discussion on the wall is given in the next section.

Table I

Parameter Range of the 0.3m TCT

- Continuous Running
- $20 \times 60cm$ slotted test section
- Operating total pressure 1.1 to 6.12 atm.
- Operating total temperature 77.4 to 340°K
- Mach number 0.02 to 0.94
- Re/m 0.4 to 400 million

3. ARL Mach 3 Tunnel

The Aeronautical Research Lab (ARL) tunnel is located in the Wright-Patterson Air Force Base in Dayton, Ohio. It is an intermittent (blow-down) tunnel with no total temperature control. At nominal tunnel Mach number of 3.0 the unit Reynolds number can be carried from 20×10^6 to 95×10^6 per foot. The test section is $8'' \times 8.2'' \times 24''$. The measurements were made at average stagnation temperature of 480^oR and at three nominal stagnation pressures of 85, 240, 400, 505 and 560 psia. The corresponding free stream Reynolds numbers were 18.6×10^6 to 93×10^6 per foot. More details on the ARL Mach 3 tunnel could be found in Reference 12.

IV. MEASUREMENTS AND DISCUSSIONS

Tests in the Unitary Plan Wind Tunnel of NASA Langley were the first attempt to conduct systematic measurements by six different transducers, simultaneously. Previous measurements in this tunnel by J. M. Allen (Ref. 13) using various techniques had resulted in a large number of skin friction data specifically at the same measurements location and flow conditions. A window in the tunnel wall had been replaced with a solid plate on which different transducers were flush mounted. Figure 5 is a photo taken from this plate and shows the relative position of the different transducers. There were three floating element balances, two surface hot film sensors and our belt skin friction transducer. The tests were sponsored by the NASA IRD

to evaluate the surface hot film sensors against the floating element balances, which in turn had (floating) elements of different sizes and materials. Therefore, the measurements by the BSFB was on a piggy back basis and had no influence on the run conditions.

Many runs were made at a nominal Mach number of 2.16 for various Reynolds numbers $Re/ft = 0.5 \times 10^6$ to 11×10^6, at $T_t = 125^oF$. The measurement results were plotted on the graph containing the data by Allen (Ref. 13) as shown in Figure 6. Allen has used the Van-Driest's technique to convert the data to incompressible values in order to compare the measurements to that of an incompressible flat plate. The agreements between the measurements made by our BSFB and Allen's data appear to be quite good for the high Reynolds number range.

At low Reynolds numbers there appear to be some scatter in all of the data. This is attributed to two possibilities: 1) The tunnel flow may not be quite uniform and steady, 2) The load corresponding to the low Reynolds number falls in the lower design range of our transducer. In addition to the above two reasons, we experienced another source of error. This happened due to evacuation of the tunnel which sucked small particles, from the sealing clay around our transducer, into this instrument and resulted in a small zero shift. At low Reynolds numbers the small zero shift influenced the data more. The contamination was identified only when the transducer was removed to be inspected for damages causing a zero shift. It is desirable to repeat these measurements, if possible, in the future.

Variations in Reynolds numbers were accomplished by changing the total pressure in the unitary plan tunnel. The strip chart recording made during transition from one total pressure to another indicates the corresponding transient readings by our transducer as shown in Figure 7. Since there were intentionally no damping provided, one can see the small (symmetric) influence of tunnel vibration on the transducer output.

Similarly measurements were made with the BSFB instrument in the 0.3m cryogenic tunnel of the NASA Langley Research Center. The 0.3m cryogenic tunnel has a very wide range of Reynolds numbers as stated in Table I. The tunnel total temperature was varied over a wide range of $T = 300^oK$ to $T = 100^oK$. The operating temperature range of the tunnel during these measurements was beyond the range for which the BSFB

instruments strain gages were temperature compensated. Therefore, the instrument was calibrated at various temperatures for which measurements were to be made. These calibrations represented linear functions of output vs. input for each temperature.

The data shown in Figure 8 were also measured during a special test designed to exercise a number of new instrumentation techniques in a high pressure, transonic, cryogenic environment. To insure a minimum of disturbance during these tests, there was no model mounted in the tunnel, and extra time was allowed for data acquisition to allow repeat points and to minimize temperature gradients. Since the skin friction measurements were to be taken on the tunnel sidewall, special care was also used in fitting the sidewall components to minimize boundary layer disturbances. However, the data in Figure 8 exhibits a rough wall trend, i.e., very little change in C_f with increasing Reynolds number. It is instructive to consider the distributed wall roughness height which might predict the observed data.

The phenomena of rough flat-plate flow is discussed by White (Ref. 14) where an approximation for C_f in the fully rough regime is presented as

$$C_f = (2.87 + 1.58 log\left(\frac{x}{\epsilon}\right))^{-2.5}$$

where x is a characteristic length and ϵ is roughness height. A wind tunnel wall is not a perfect representation of a flat plate since there is no leading edge and the turbulent boundary layer is preceded by a run of high pressure gradient flow in the contraction section. Thus, in order to properly utilize the above expression, it is necessary to establish a virtual origin for the turbulent boundary layer which will define a characteristic length, x, and a meaningful ratio of length to roughness height, x/ϵ.

Reference 15, presents measured values of boundary layer, displacement, and momentum thickness for the 0.3-m TCT as a function of freestream Mach and Reynolds number. This information allows the determination of Re_δ which together with the relation

$$Re_\delta = 0.16(Re_x)^{6/7}$$

from reference 14, permits calculation of Re_x, and finally the calculation of x from

$$x = \frac{Re_x}{Re_{(m^{-1})}}.$$

Substitution of this value into the expression for C_f now yields a value for each distributed roughness height selected. (Note that this formulation for x reintroduces a Reynolds number dependence into the expression for C_f). Curves representing a range of values for roughness height are plotted in Figure 9 , and values in the range from 0.005 to 0.02 mm (0.0002 to 0.0008 inches) are typical of the data.

Even though joints between component parts are being represented by a distributed sand type roughness in this analysis, it is obvious that small disturbances will produce the trends shown by the data in Figure 9. Also, when considering that this data was taken over large changes in temperature and pressure, which would cause small changes in the relative positions of the components, it is not surprising that the lowest temperatures lie in a band unto themselves. Finally, the classic approximation for smooth wall skin friction

$$C_f = 0.027/(Re_x)^{1/7}$$

is shown, and is seen to approach the measured data at the lower Reynolds numbers which were obtained at conditions near atmospheric pressure and ambient temperature.

Measurements in the ARL Mach three tunnel were performed in cooperation with the Experimental Engineering Branch, on a piggy-back basis. There has been an ongoing development project on a floating element direct skin friction measuring balance for the past three years. The balance that was used was the same NASA balance used in the other tunnels and developed by Tcheng (Ref. 16), with a heater built into the balance to warm up various internal components and to reduce potential damage and thermal drift. The BSFB transducer was the same one used in the previous measurements with no modifications except that it was cleaned thoroughly.

The two transducers were installed on the tunnel floor at the downstream of the nozzle where the wall represent approximately a flat plate. The tunnel flow parameters and the transducers output were sampled throughout each run by the data acquisition computer. The transducers output along with the the signal from an accelerometer mounted on the tunnel wall were recorded on a galvanometer type strip chart recorder at speeds up to 80 inches per second. There were thermocouples installed inside each transducer which were also recorded by the data acquisition system and the

strip chart recorder. This was to identify the operating temperature of each instrument for possible corrections.

Typical run times were in order of 30 seconds during which the tunnel total temperature dropped nearly 30°C. The modified NASA balance required a one to ten minute warm-up time (by the heater) in between the runs. Figure 10 shows a plot of the data measured in the ARL tunnel for the two transducers. The agreement appears to be reasonably good with the NASA balance slightly higher even when compared with the Van Driest (Ref. 15) flat plate theory for compressible flow. Each data point plotted represent at least twenty data points.

In order to investigate the influence of temperature drop (heat transfer) on the performance of the two transducers, the ARL tunnel was operated during one run, with the tunnel stagnation pressure $P_t = 240$ psia, for 50 seconds. A comparison of the skin friction coefficients measured by the two transducers and the theoretical prediction by VanDriest (Ref. 17, 18) for various temperature ratios is shown in Figure 11. As has been observed before, the data by the BSFB appear to lie closer to the flat plate theoretical line. Figure 12 shows a typical section of the strip-chart recorder indicating the trends in the two transducer signals and the vibration signal by the accelerometer transducer. It is noteworthy to compare the effect of the tunnel starting shock as well as the stopping shock on the two signal. It appears that the BSFB transducer has a better dynamic response, as expected.

IV. CONCLUSIONS AND RECOMMENDATIONS

A relatively small belt skin friction balance instrument has been developed for direct measurement of the wall shear stresses exerted by fluids on submerged moving surfaces. This transducer consists of a flexible belt wrapped continuously and tightly over two partial cylinders which are mounted on frictionless flexures. A portion of the belt replaces a small area of the body over which the fluid flows.

Due to its design simplicity, most of problems associated with direct measurement of skin friction by the floating element balances are minimized or eliminated.

Measurements have been made in various wind tunnels and compar-

isons have been made with available data and other direct measurement and theoretical techniques. In general, excellent agreement is observed between measurements made with the present balance and data available for approximate flat plate flows.

An optical displacement detection technique has been incorporated into a prototype instrument successfully. This technique is very promising and can result in a significant increase in sensitivity and may eliminate the temperature effects. Optical techniques will also enable reductions in overall dimensions of the belt skin friction balance. Further work is recommended to optimize the optical components to be incorporated into the belt skin friction balance.

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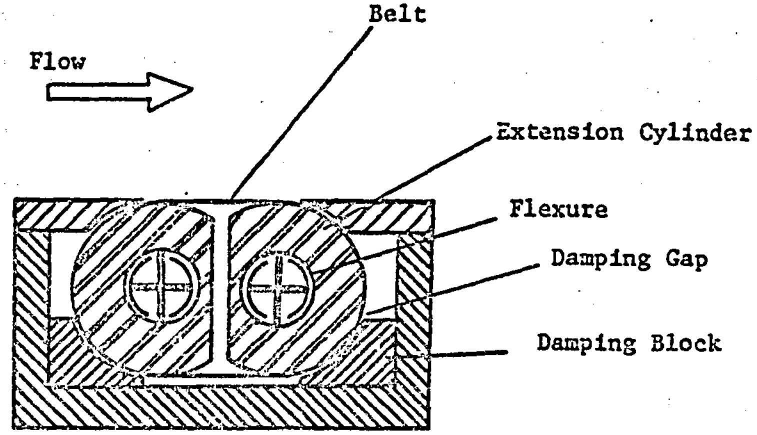
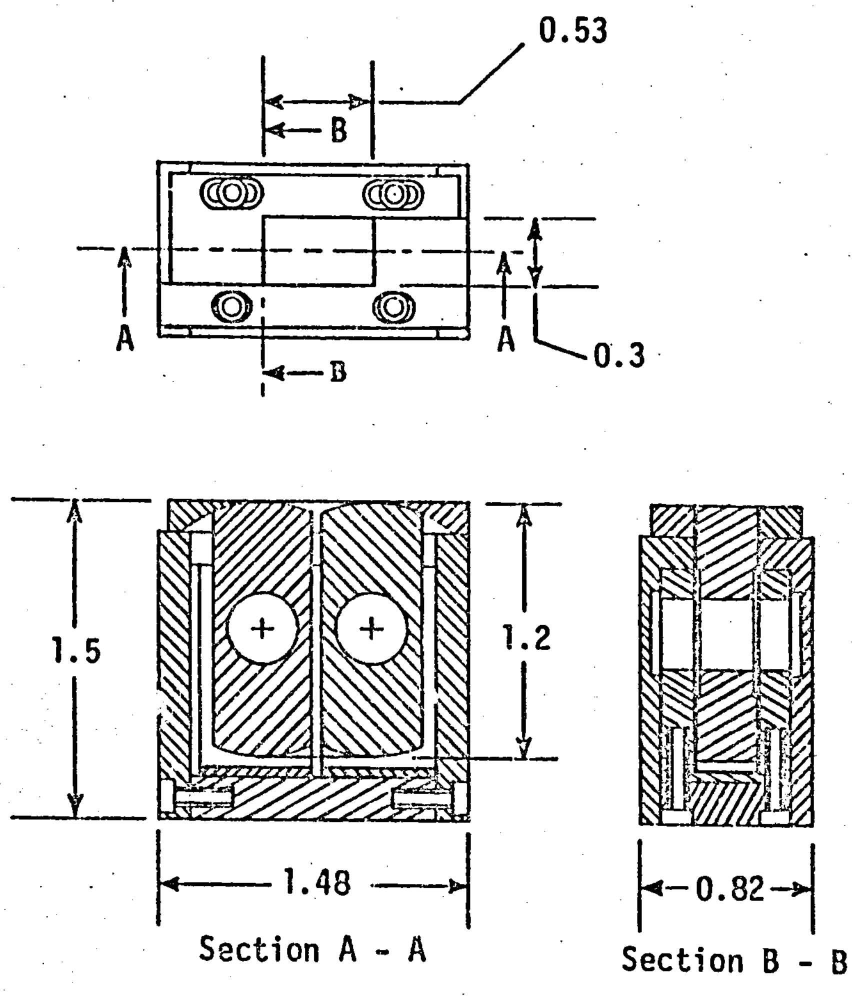


Figure 1: Belt Skin Friction Balance, Schematic Showing Principles of Operation.

All Dimensions Are Inches



Sections of the Modified Skin
Friction Transducer

Figure 2. Dimensions and details of the compact version of the Belt Skin Friction Balance.

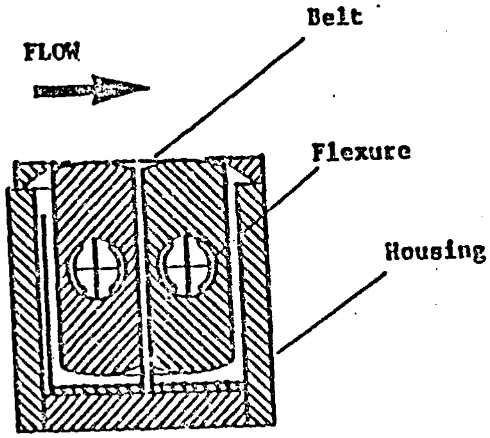
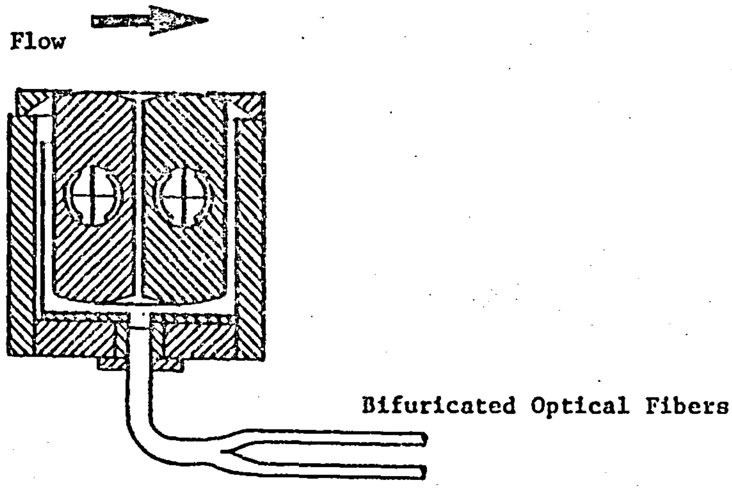
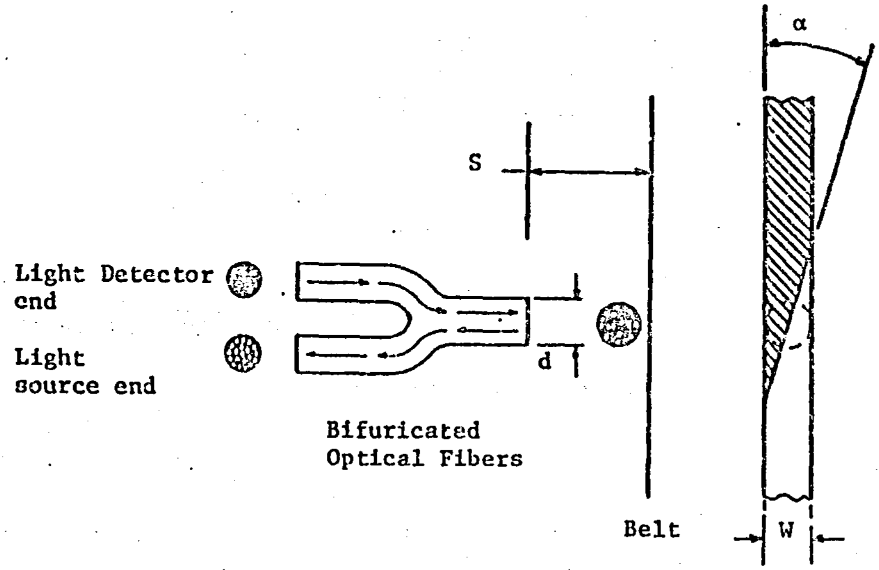


Figure 2. Continuded



a. Interface of Optical Fibers in the instrument.



b. Detail of the Optical Sensing technique.

Figure 3. Fiber Optics Sensing Mechanism for the UTSI BSFB.

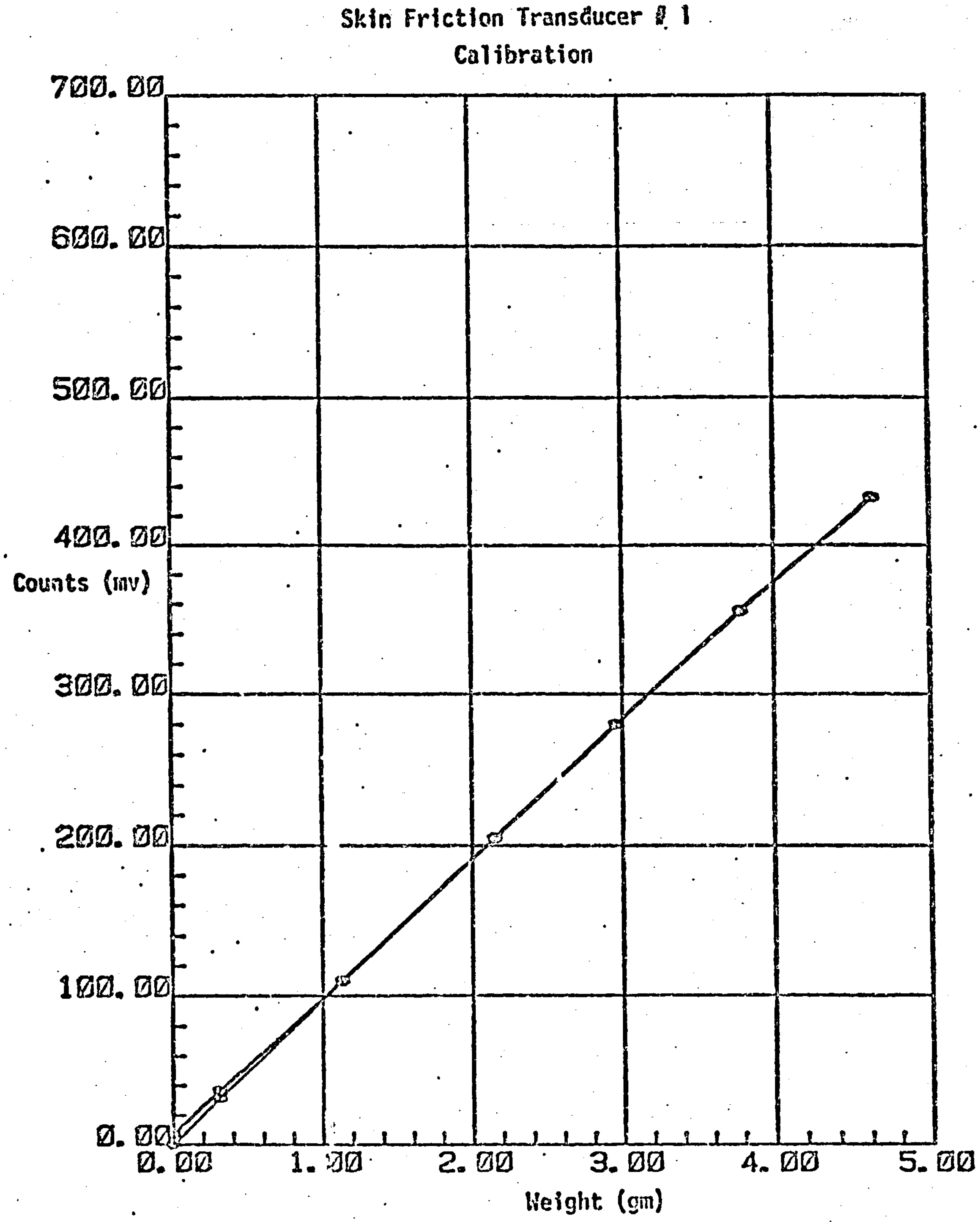


Figure 4. Typical Calibration of the BSFB.

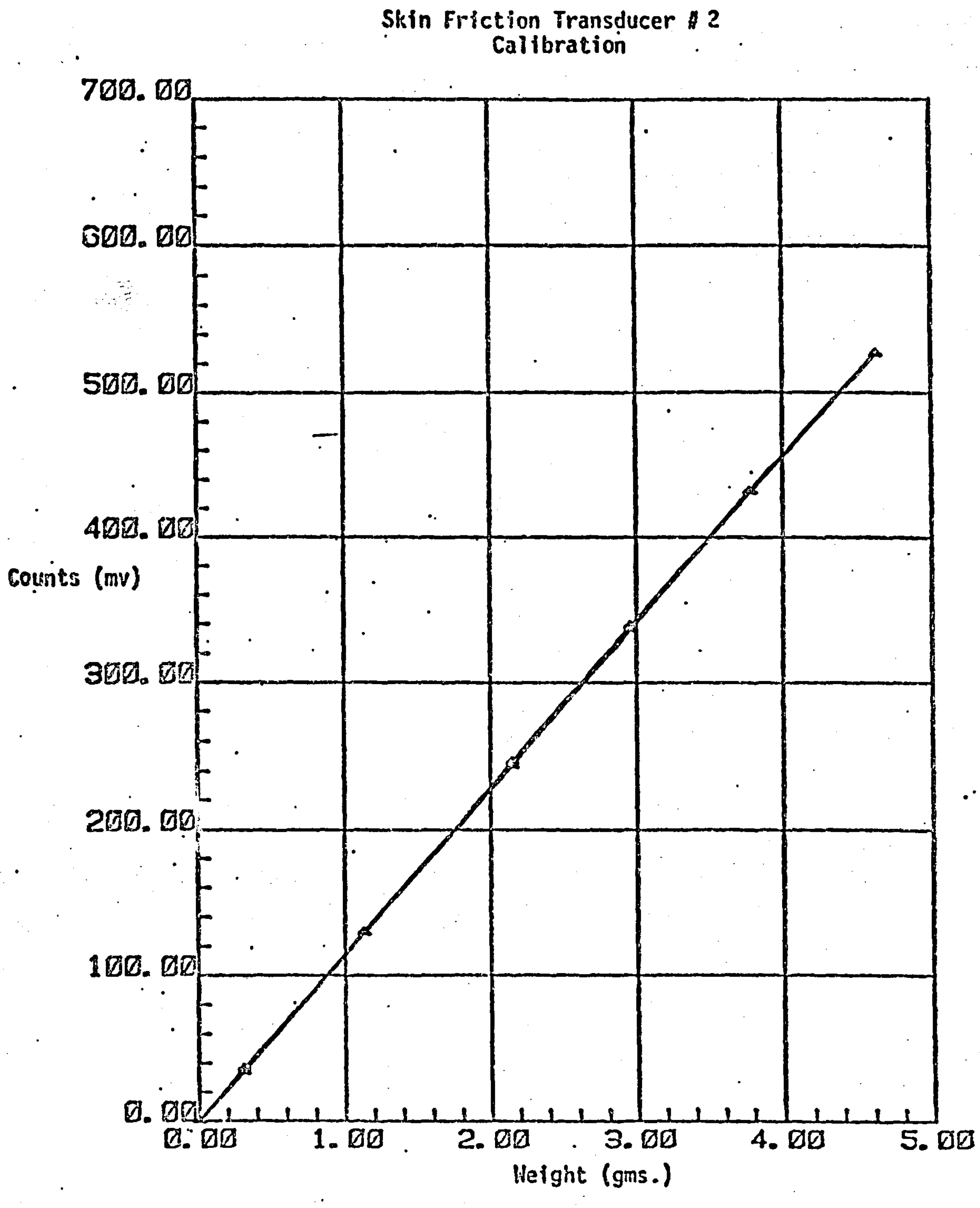


Figure 4. Continued

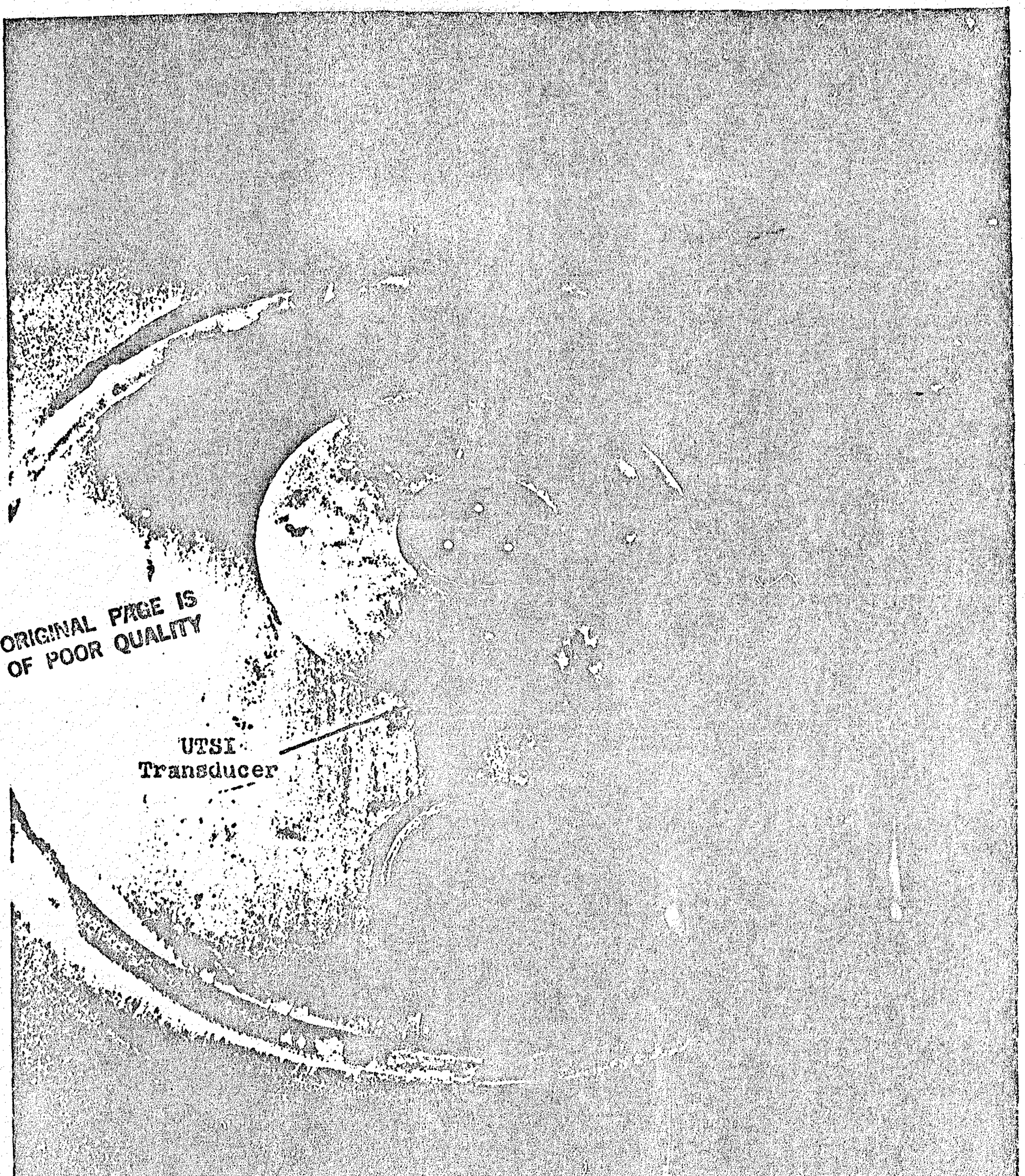


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Figure 5. Measurement configuration of the UTSI transducer on the Unitary Tunnel Wall.

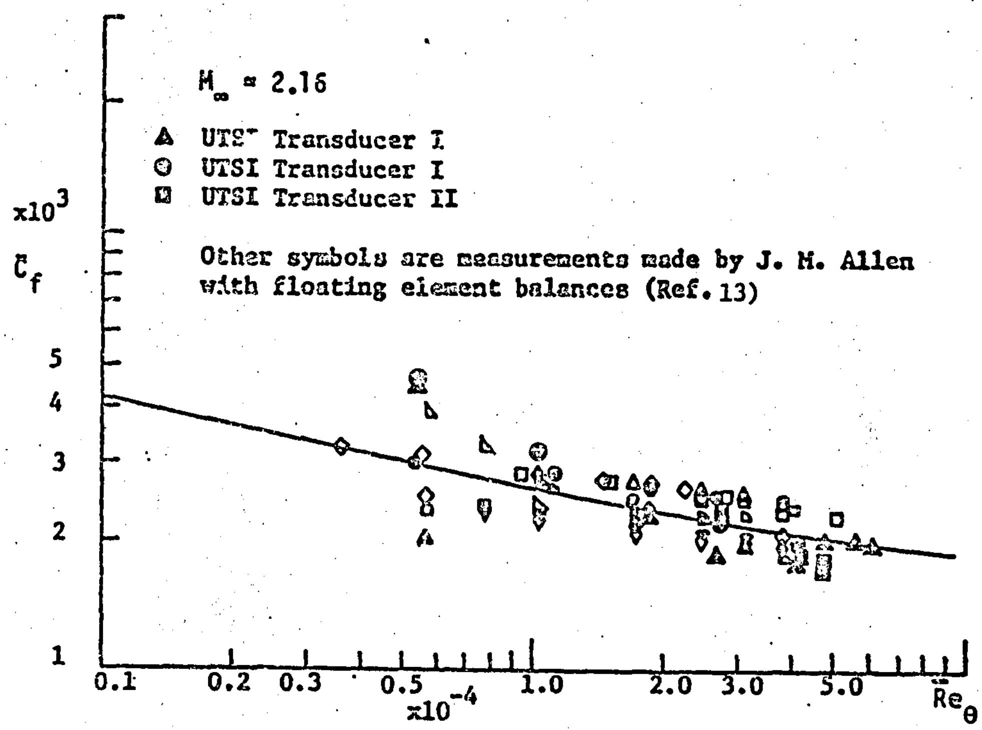

Figure 6. Direct Wall Shear Stress Coefficient (incompressible) Measured in the NASA Langley Unitary Wind Tunnel.

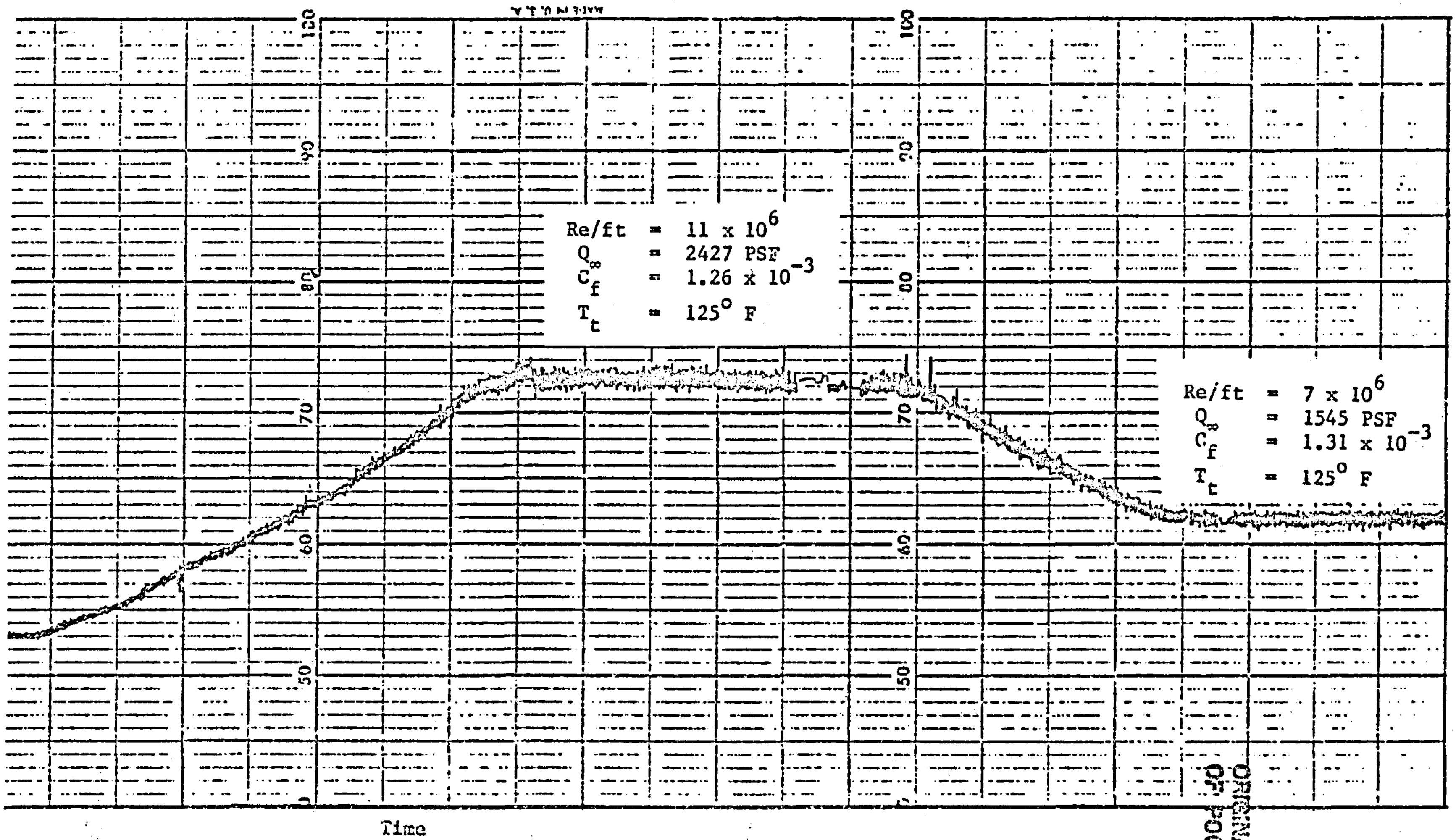

Figure 7. Transient Oscillograph Recording of the BSFB with Variations in the Tunnel Operating Conditions.

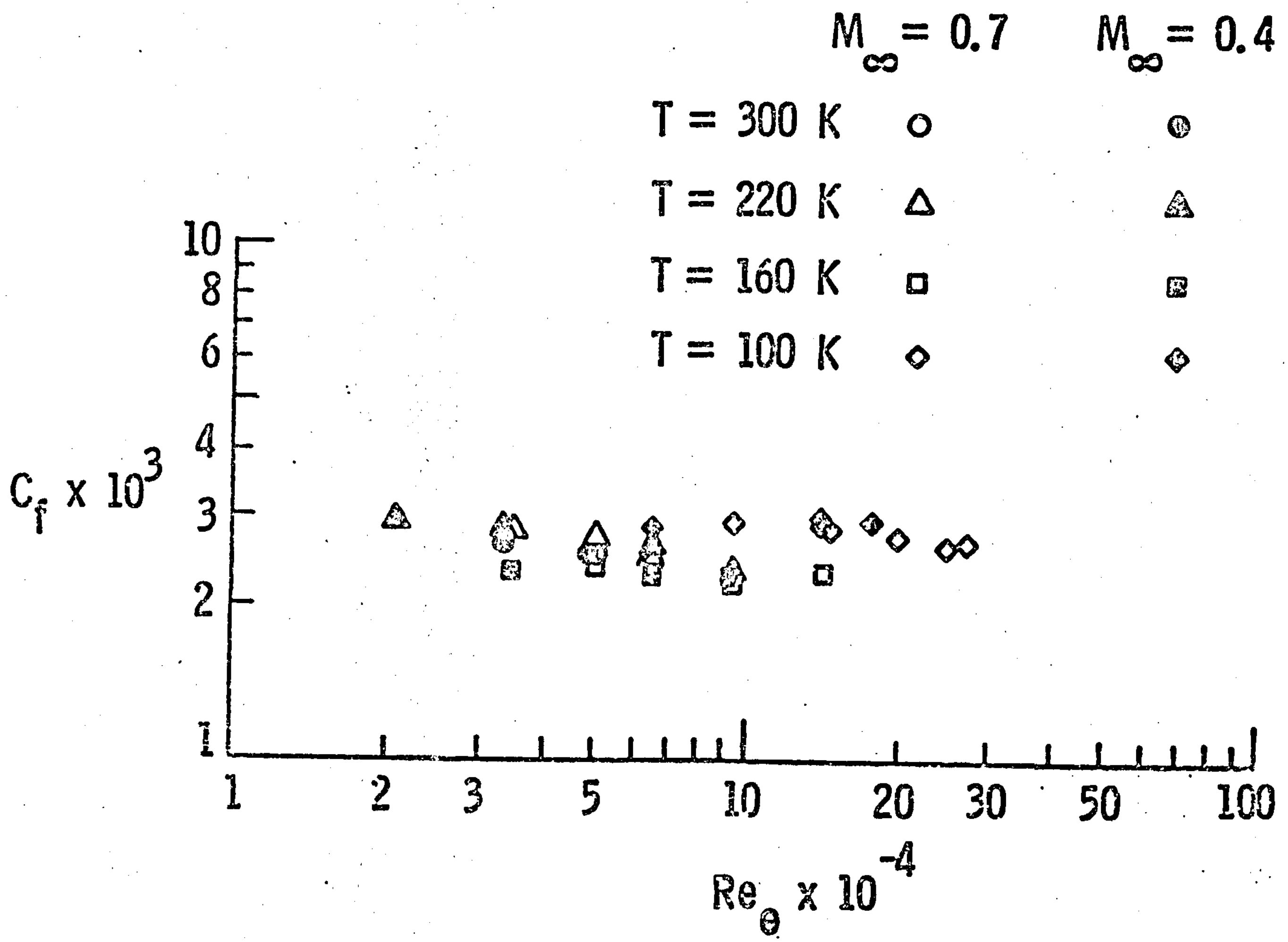

Figure 8. Wall Shear Stress Measurements in the NASA Langley 0.3-m Transonic Cryogenic Tunnel at Different Total Temperatures.

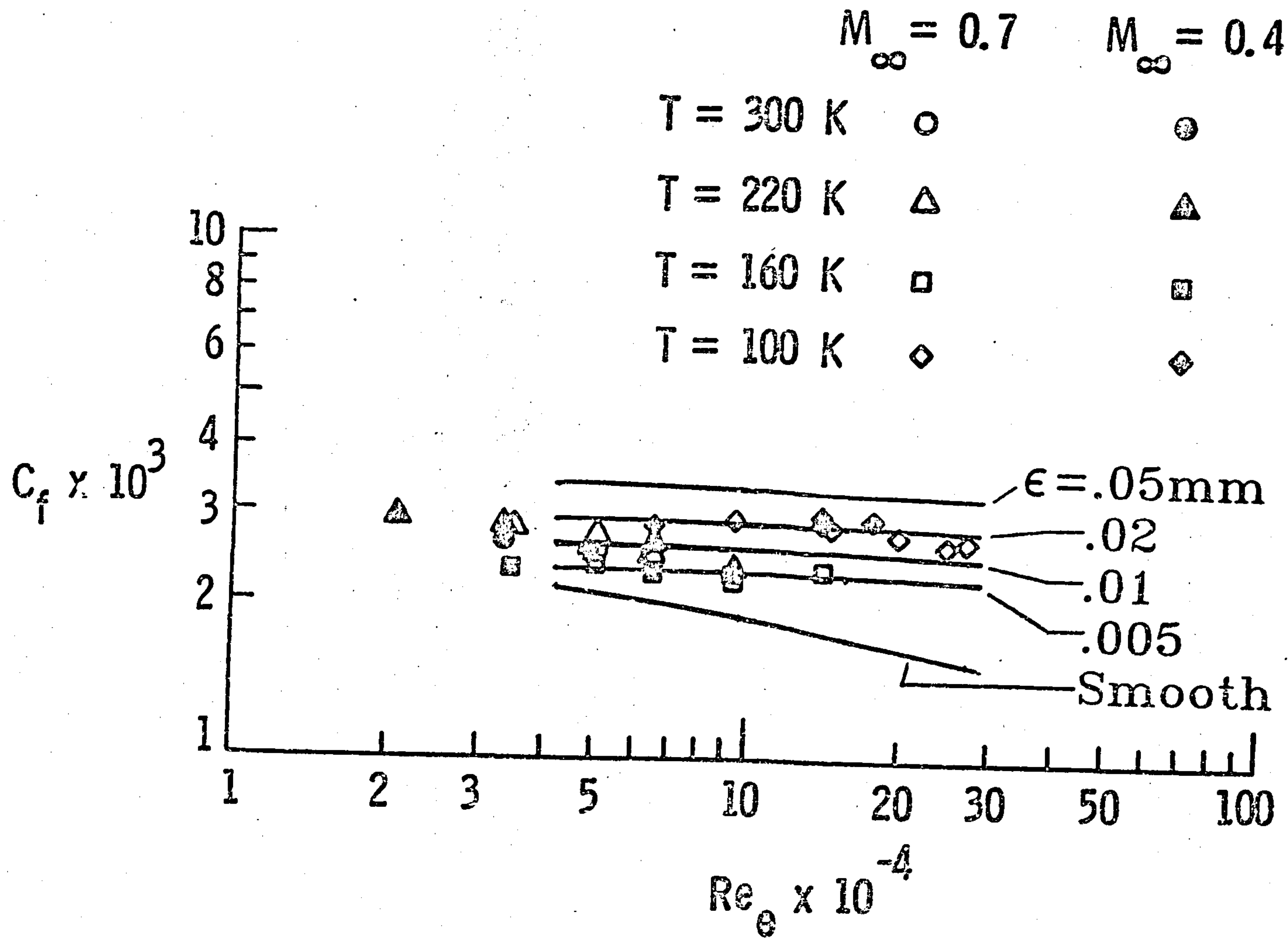

Figure 9. Wall Shear Stress measured on the 0.3-m TCT side wall and comparison with predictions (Reference 14).

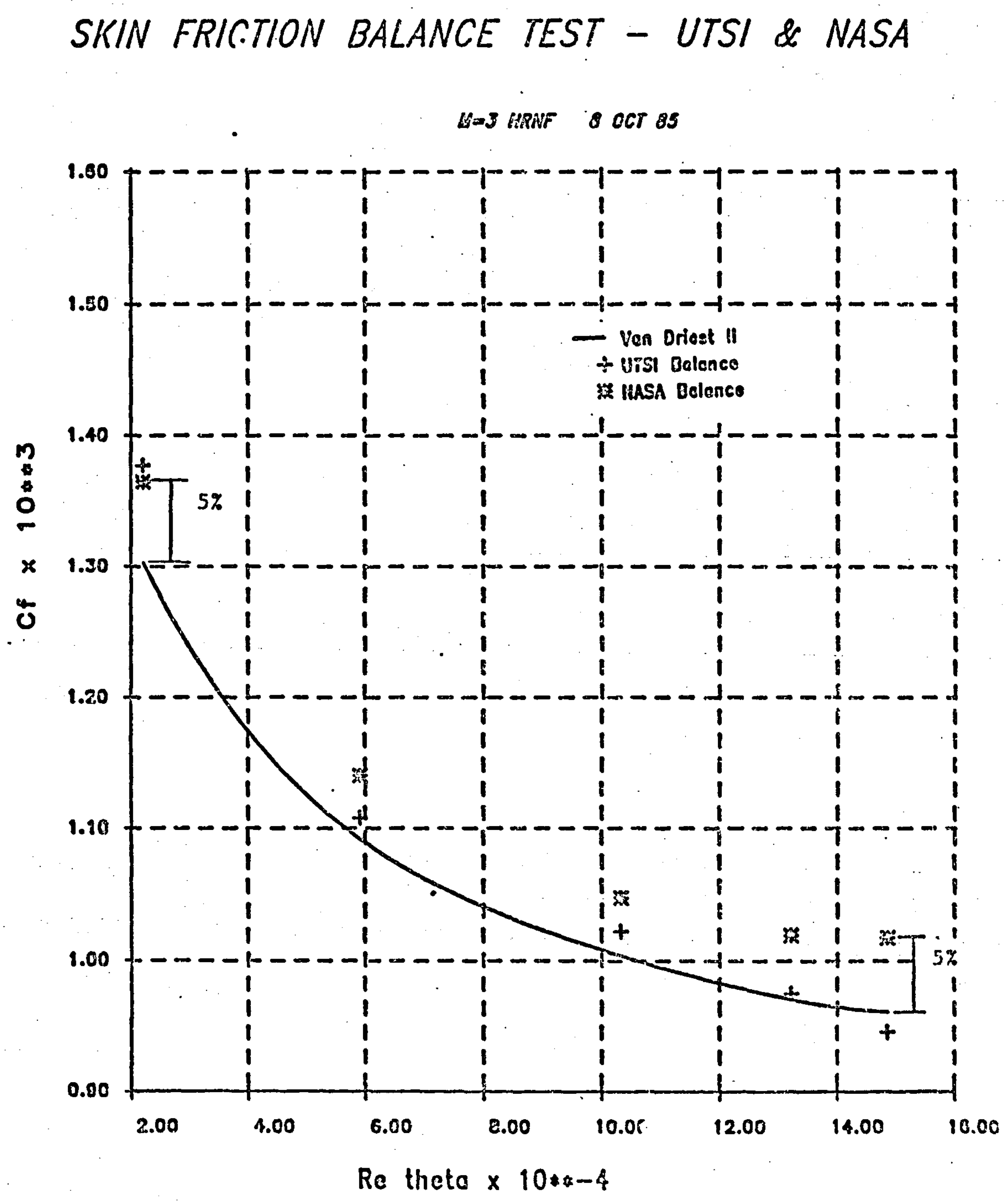

Figure 10. Direct Shear Stress Measurements in the ARL Mach 3 Tunnel.

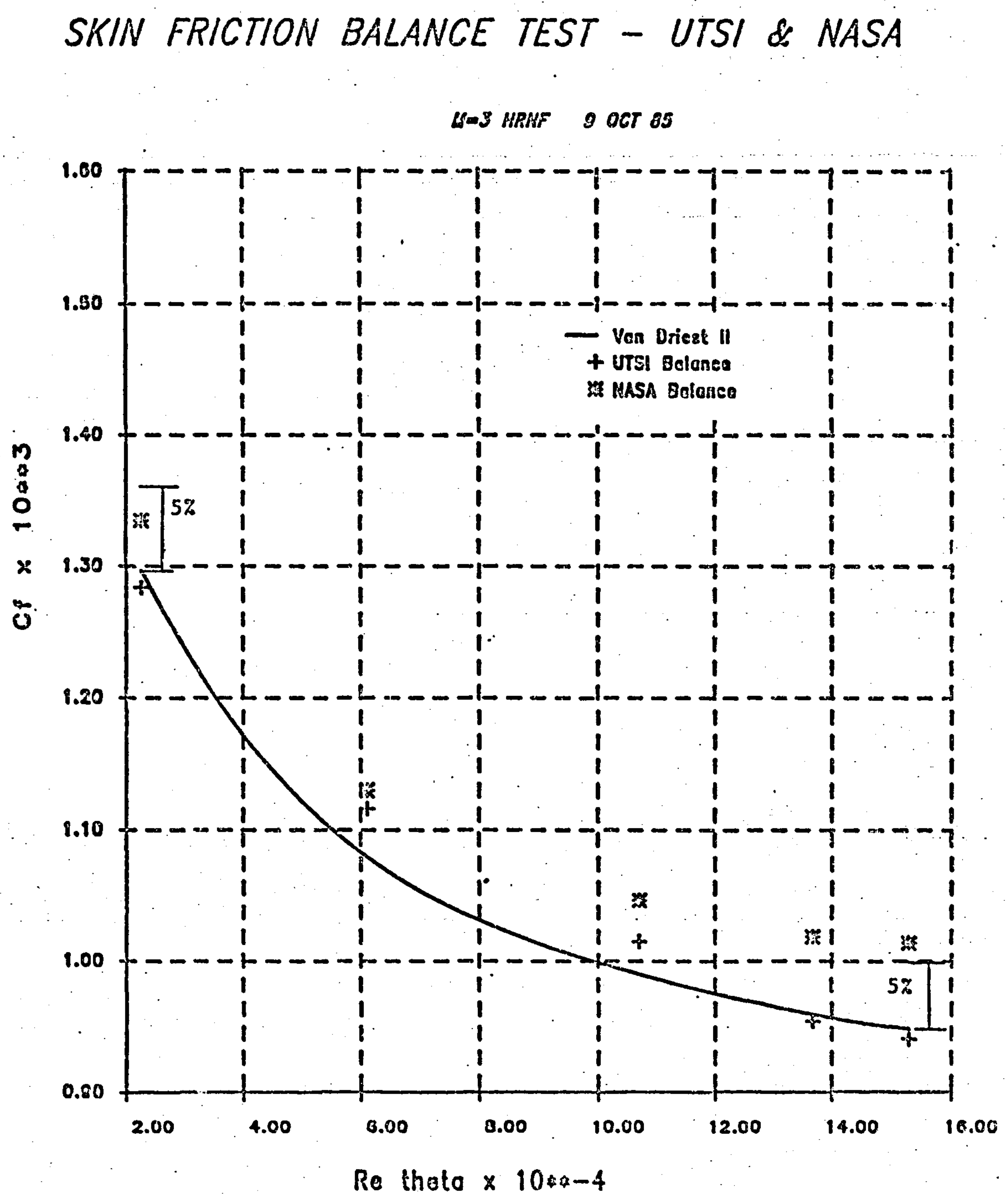

Figure 10. Continued

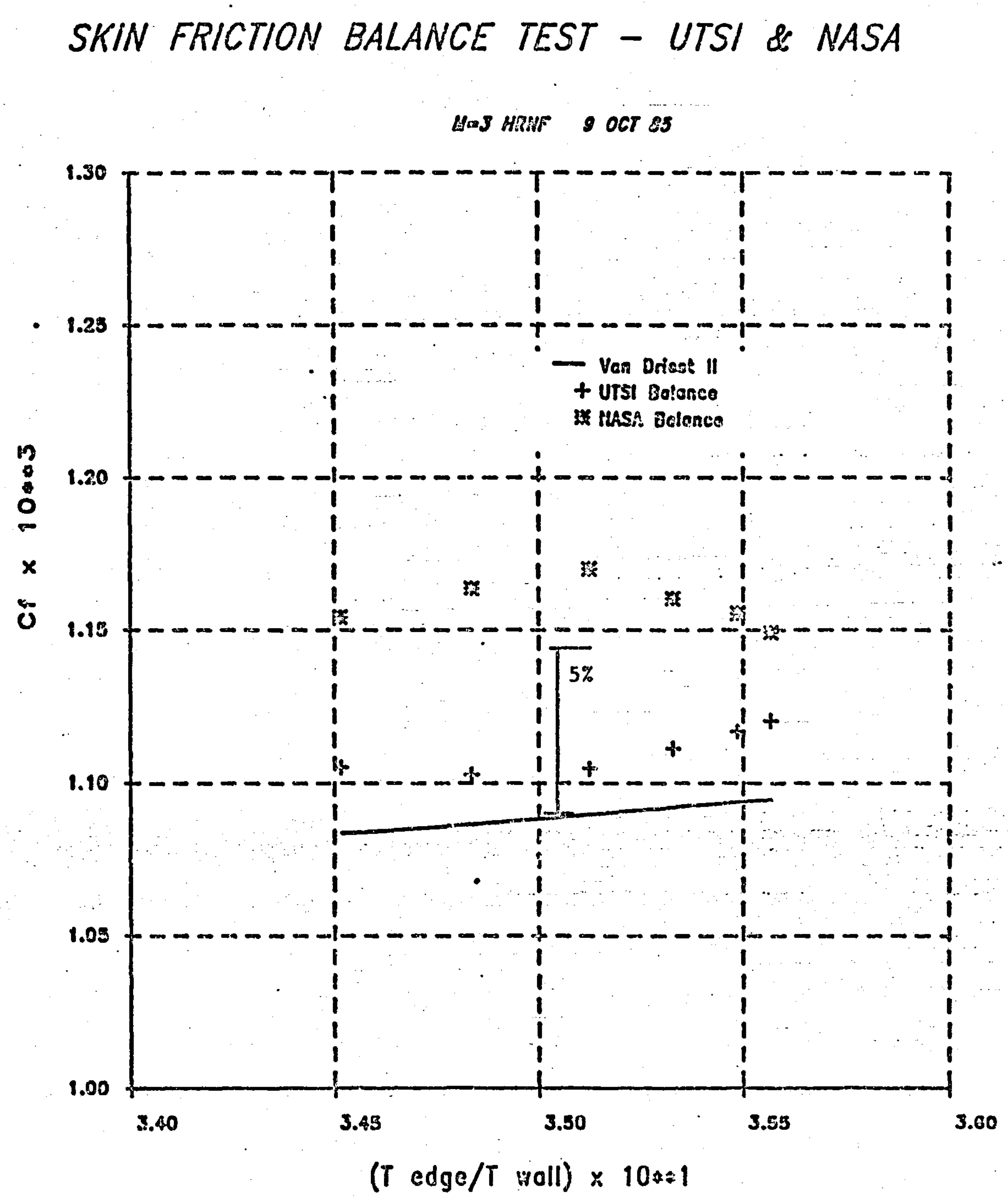

Figure 11. Wall Shear Stress Measurements and Comparison with theory in presence of Heat Transfer.

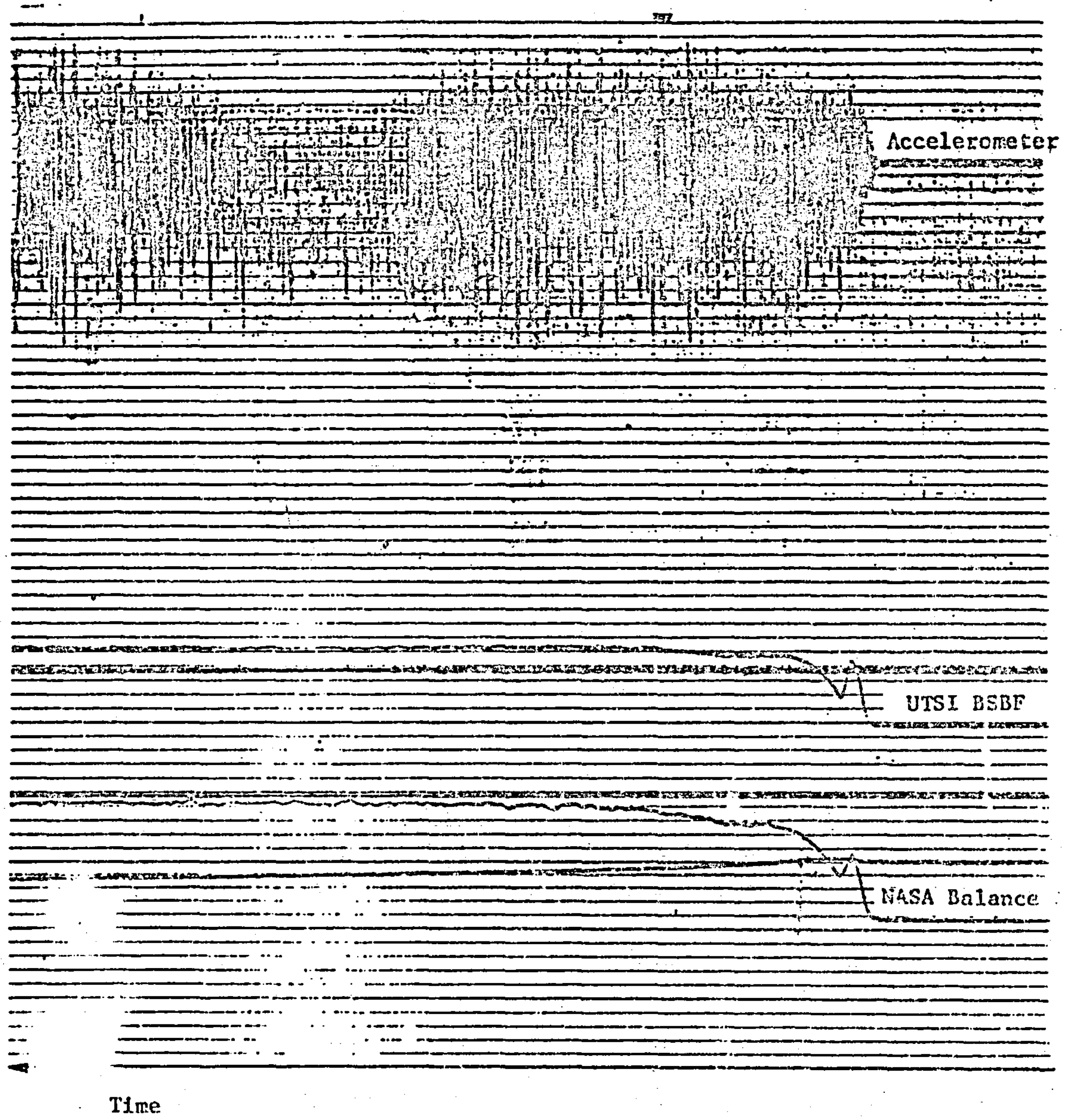

Figure 12. Oscillograph trace of the UTSI BSBF, NASA Balance, and an accelerometer in the ARL Ma ' Tunnel, during the Tunnel starting time.

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